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EP 0721241 A   EP 0690516 A   US 5569934 A
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et al pp121-126

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(54) Abstract Title
An LED based on a two well system with charge asymmetric resonance tunnelling

(57) An LED for example, a GaN, GaAs, ZnSe or AlGaInP based LED, comprises a two well system with charge asymmetric resonance tunnelling. The two wells form first and second coupled wells. One well is a wide well and the other is an active quantum well. The wells are coupled via a resonance tunnelling barrier which is transparent for electrons and blocking for holes. The active well may be a multiple quantum well (MQW) structure. The wide well may be a simple undoped electron emitting layer, or an MQW. The buffer layer may be a strained superlattice. A p-contact may be made from GaN, p-$Al_xGa_{1-x}N$ or p-type polycrystalline GaN. The p-layer may be codoped using one or both of Mg and Al. The substrate can be removed by wet etching or laser ablation.
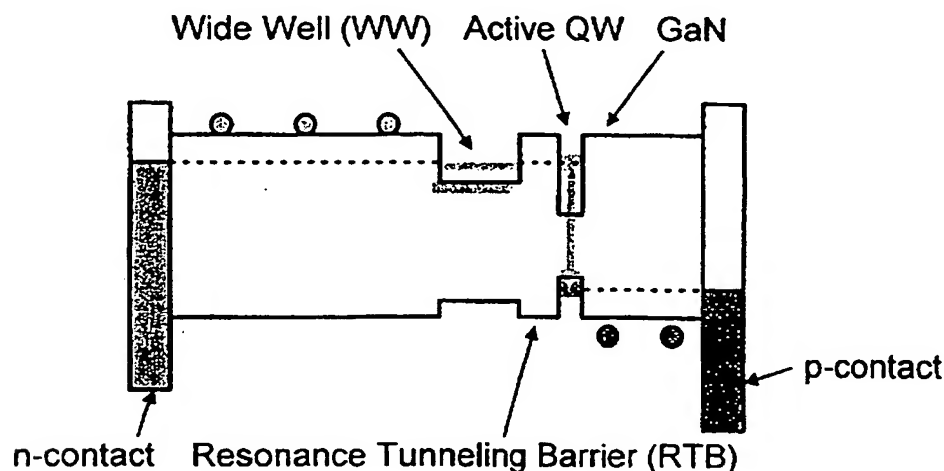
Wide Well (WW)   Active QW   GaN

n-contact   Resonance Tunneling Barrier (RTB)   p-contact

FIG. 2

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an n-type GaAs substrate with the thickness of 100-300 μm;

a metallic ohmic contact attached to the substrate;

an n-type GaAs buffer layer with a doping level of 5×10^{17} - 10^{19} cm^{-3} and a thickness of 0.1 to 0.3 μm;

an n-cladding layer made of 0.3 to 2 μm thick n-type $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0.5 \leq x \leq 1$ and a doping level of 5×10^{17} - 10^{20} cm^{-3};

an electron emitting layer comprising a simple undoped electron emitting layer made of 0.01 to 0.2 μm thick $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0.2 \leq x \leq 0.5$ or a multiple quantum well structure made of < 1 μm thick $(Al_xGa_{1-x})_{1-y}In_yP$ / $(Al_{x1}Ga_{1-x1})_{1-y1}In_{y1}P$ with $0.5 \leq x \leq 1$, $0.4 \leq y \leq 0.6$ and $0 \leq x1 \leq 0.4$, $0 \leq y1 \leq 0.4$;

a charge asymmetric resonance tunneling barrier comprising an ~10-100 Å thick undoped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layer with $0.7 \leq x \leq 1$;

an active well layer comprising either a single quantum well structure made of <200 Å thick undoped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0 \leq x \leq 0.4$ or a multiple quantum well structure made of $< 1\mu$m thick $(Al_xGa_{1-x})_{1-y}In_yP$ / $(Al_{x1}Ga_{1-x1})_{1-y1}In_{y1}P$ with $0.5 \leq x \leq 1$, $0.4 \leq y \leq 0.6$ and $0 \leq x1 \leq 0.4$, $0 \leq y1 \leq 0.4$;

a 0.3 to 1 μm thick hole emitting layer made of p-type $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0.5 \leq x \leq 1$ and a doping level of 5×10^{16} to 10^{18} cm^{-3} ;

a ≤ 12 μm window layer made of p-type $In_xGa_{1-x}P$ with $x \leq 0.1$ and a doping level 5×10^{17} to 5×10^{18} cm^{-3}; and

a metallic ohmic contact deposited on the hole emitting layer.

Application No: GB 0012550.0   **Examiner:** Claire Williams

Claims searched: all   **Date of search:** 10 November 2000

Patents Act 1977
Amended Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

     UK Cl (Ed.R): H1K (KEE, KEAA, KEAX)

     Int Cl (Ed.7): H01L 33/00

Other: ONLINE: WPI, EPODOC, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	EP 0721241 A1 (CANON) in particular Figure 1 and page 4 lines 7 to 15	1, 4, 9
X	EP 0690516 A1 (SHARP) in particular page 5 lines 37 to 40, and page 6 lines 7 to 11	1, 4, 9
X	US 5569934 (FUJII) in particular Figure 6b, and claim 1	1
A	Physica Status Solidi (a), Vol 180, No.1, (2000), Rebane et al, "Light emitting Diode with Charge Asymmetric Resonance Tunneling", pp121-126 , whole document	

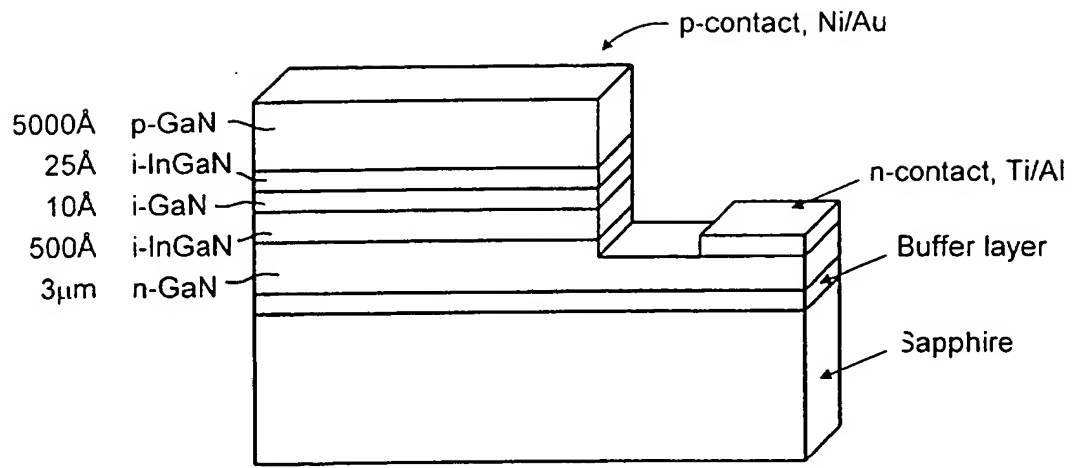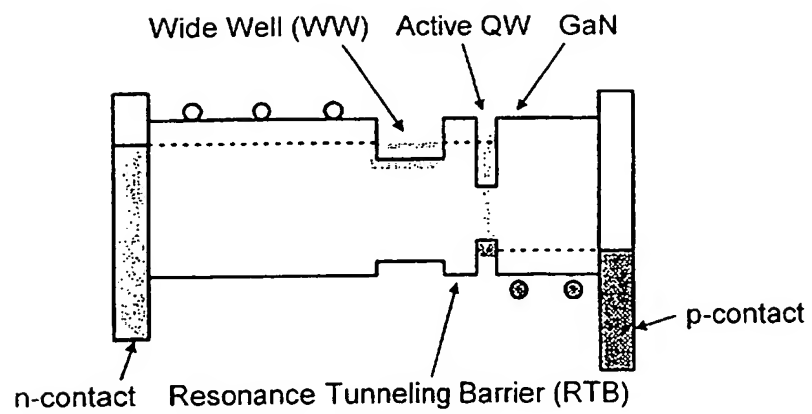|			
X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

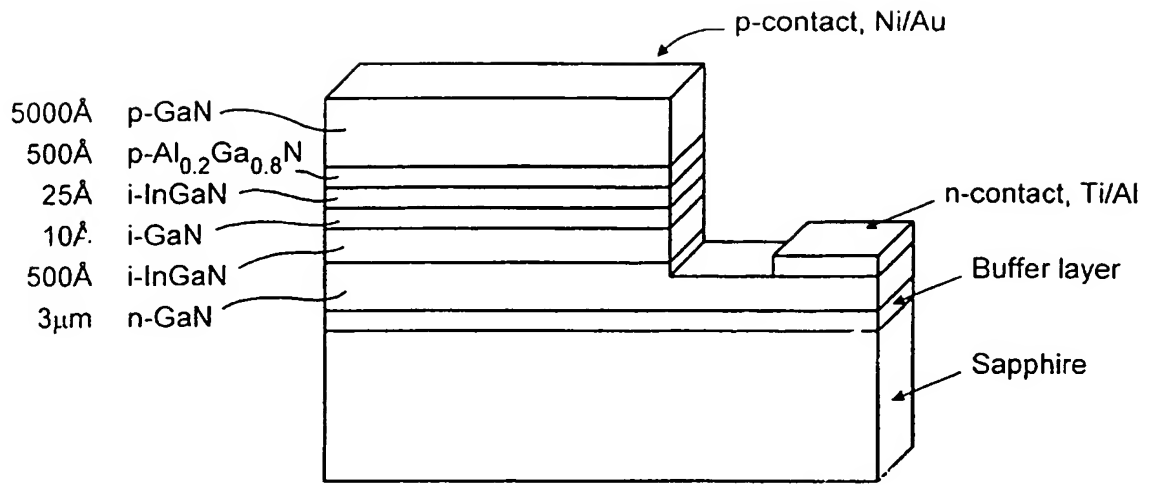p-contact, Ni/Au

5000Å p-GaN
25Å   i-InGaN
10Å   i-GaN
500Å   i-InGaN
3μm   n-GaN

n-contact, Ti/Al

Buffer layer

Sapphire

FIG. 1

Wide Well (WW)   Active QW   GaN

n-contact   Resonance Tunneling Barrier (RTB)

p-contact

FIG. 2

p-contact, Ni/Au

5000Å p-GaN

500Å p-Al$_{0.2}$Ga$_{0.8}$N

25Å i-InGaN

10Å i-GaN

500Å i-InGaN

3μm n-GaN

n-contact, Ti/Al

Buffer layer

Sapphire

FIG. 3

Wide Well Electron Accumulating Layer (EAL)

Active QW

AlGaN

GaN

p-contact

n-contact

Resonance Tunneling Barrier (RTB)

FIG. 4

p-contact, Ni/Au

1000Å   p-AlGaN
25Å   i-InGaN
10Å   i-GaN
500Å   i-InGaN
3μm   n-GaN

n-contact, Ti/Al

Buffer layer

Sapphire

FIG. 5

Wide Well
Electron
Accumulating
Layer (EAL)

Active QW

$Al_{0.1}Ga_{0.9}N$

p-contact

n-contact   Resonance Tunneling Barrier (RTB)

FIG. 6

1000Å polycrystalline p-GaN

p-contact, Ni/Au

5000Å p-GaN

25Å i-InGaN

10Å i-GaN

500Å i-InGaN

3μm n-GaN

n-contact, Ti/Al

Buffer layer

Sapphire

FIG. 7

p-contact

$p\text{-}In_xGa_{1-x}P$

$p\text{-}(Al_xGa_{1-x})_{0.5}In_{0.5}P$

$(Al_xGa_{1-x})_{0.5}In_{0.5}P$

$(Al_xGa_{1-x})_{0.5}In_{0.5}P$

$n\text{-}type(Al_xGa_{1-x})_{0.5}In_{0.5}P$

0.3 μm n-GaAs

300 μm n-GaAs substrate

n-contact

FIG. 8

p-contact, Ni/Au

5000Å p-GaN

500Å $p\text{-}Al_{0.2}Ga_{0.8}N$

25Å i-InGaN

10Å i-GaN

500Å i-InGaN

50μm n-GaN

n-type Buffer layer

n-contact, Ti/Al

FIG. 9

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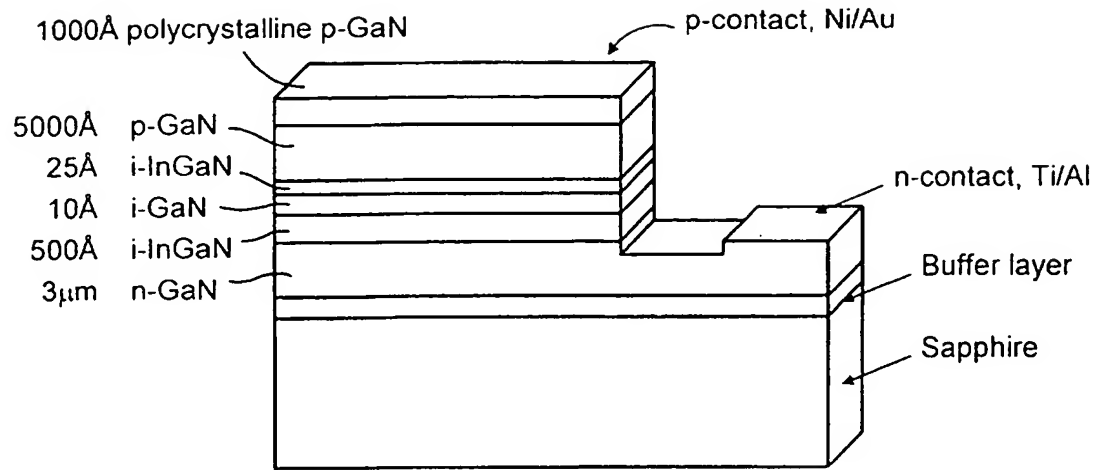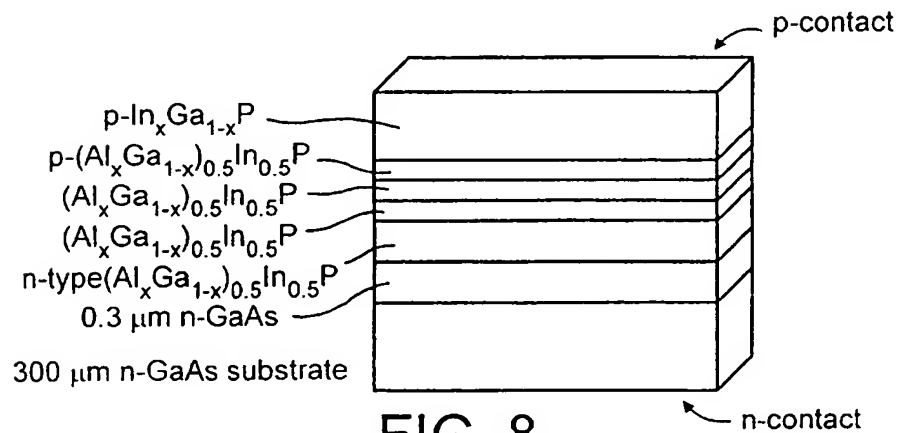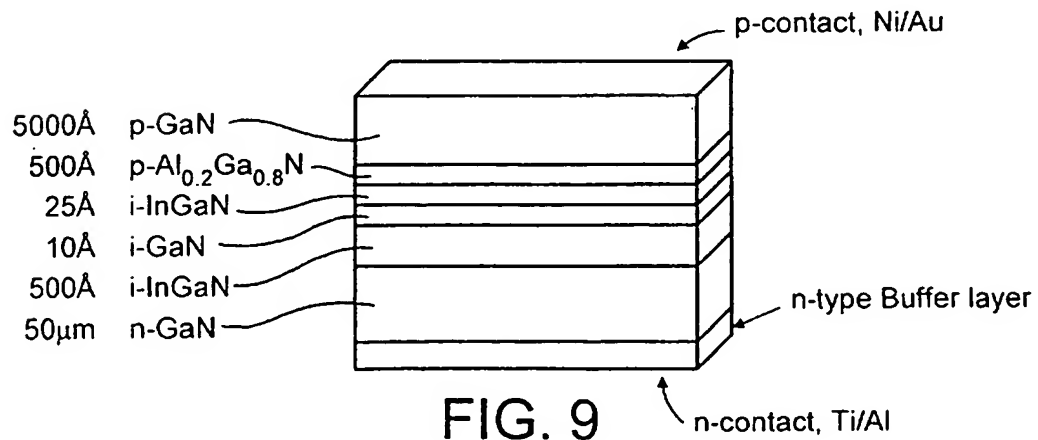
LIGHT EMITTING DIODES WITH ASYMMETRIC RESONANCE TUNNELLING

5

This invention relates to light emitting diodes (LEDs).

Semiconductor LEDs emitting red, green, blue, infrared and ultraviolet light have been marketed for many years. For light generation in LEDs, radiative recombination of

10 electrons and holes in an active layer is used. The active layer can be a usual p-n junction, heterojunction, single quantum well or multiple quantum wells. In some LEDs, a single quantum well or multiple quantum wells is or are used as the active layer. For fabrication of a highly efficient device, the number of carriers recombined inside the active layer should be maximized and the number of carriers recombined

15 outside the active layer should be minimized. This needs optimization of capture rates for electrons and holes into the active layer. Usually in semiconductors, effective masses of holes are much higher and mobilities much less than those for electrons. Therefore, some of the electrons not captured in the active layer escape the active layer and recombine outside it. This prevents fabrication of highly efficient LED devices.

20

This invention provides an LED design based on a two well system with asymmetric tunnelling, the system comprising first and second coupled wells, namely a wide well (WW) and an active quantum well (QW), the wells being coupled via a resonance tunnelling barrier (RTB) transparent for electrons and blocking for holes. Both the wide

25 well and the active quantum well can be made of either a single quantum well (SQW) structure or a multiple quantum well (MQW) structure.

This invention allows enhancement of the number of electrons captured in the active layer with the quantum well and the fabrication of highly efficient LEDs.

30

The LED could be a GaN LED, a GaAs LED, an AlGaInP or a ZnSe LED for example. More generally, the LED could be one using any III-V and II-VI group semiconductors.

If the LED is a GaN LED, the wide well could comprise InGaN, the resonance tunnelling barrier comprising GaN and the quantum well comprising InGaN.

5   A p-contact layer could be one of GaN, p-$Al_xGa_{1-x}N$ and p-type polycrystalline GaN.

A p-contact layer could have been doped by isoelectronic codoping using one or both of Mg and Al.

10   A substrate of the LED could be removable or have been removed by wet etching or laser ablation

Ohmic contacts could be on the top and bottom or both on the top of the LED structure.

15   Resonance tunnelling between two wells means that the energy position of the WW bottom has to be equal to the energy position of the sub-band minimum of the active QW. This problem may be solved by adjusting the alloy composition in the WW and the QW, and choosing a proper QW width.

20   This design is based on the mass asymmetry of electrons and holes in GaN for example.

It allows the electron sub-band position in the active QW to be fitted to the bottom of the WW and at the same time the hole sub-band minimum in the QW to be kept lower than the bottom of the WW for holes and thus forbids hole penetration without thermal

25   activation in the WW. It is important that even the small amount of thermally activated holes have no possibility to tunnel into the WW for the chosen barrier width because of their heavy mass.

Advantages

30

The structures to be described allow:

- an increase of the capture efficiency of electrons into the active QW due to direct tunnelling of electrons from the WW into the QW

- suppression of electron leakage into the p-type layer

- elimination of parasitic light generated outside the active layer

- the use of the WW as a good current spreading layer means an improvement of the quality of the active QW because of mismatch reduction (~ 4 times). The reason is that active $In_{0.2} Ga_{0.8} N$ (for example) QW growth on a highly tensile strained thin GaN barrier has a lattice parameter close that of an $In_{0.15} Ga_{0.85} N$ (for example) WW

- the WW also works as a stopping layer for threading dislocations, because of the high stress on an interface of n-GaN/$In_{0.15} Ga_{0.85} N$ (for example)

- there is no need to use electron blocking layers as an element in this technology

- reduction of the growth time, since we expect that the same quality of the active QW will be achieved for a thinner n-GaN layer for example in a GaN LED.

Finally, the structures should allow the manufacture of cheaper and more efficient LEDs than conventional ones.

This invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figs. 1, 3, 5, 7, 8 and 9 show examples of structures according to this invention; and

Figs. 2, 4 and 6 are simplified energy band diagrams of the structures of Figs. 1, 3 and 5 respectively.

Fig. 1 shows a first structure, which is a GaN blue LED design based on a two well system with asymmetric tunnelling. The system comprises two coupled wells: a wide well (WW) and an active quantum well (QW). The wells are coupled via a resonance tunnelling barrier (RTB) transparent for electrons and blocking for holes. Table 1 lists parameters for a blue LED based on the first structure. Table 2 lists parameters for a green LED based on the first structure.

Table 1.

#	Layer	Composition	Thickness	Doping(cm^{-3})
1	Buffer Layer	GaN or AlGaN/GaN strained superlattice	50~ 500 Å	UD (undoped)
2	n-contact	GaN:Si	1-5 mm	5×10^{18}-10^{20}
3	WW	InGaN (In content 15%)	500Å	UD or n-type
4	RTB	GaN	10Å	UD
5	Active QW	InGaN (In content 20%)	25Å	UD
6	p-contact	GaN:Mg or GaN:Mg + Al	0.5 μm	~10^{18}

Table 2.

#	Layer	Composition	Thickness	Doping(cm^{-3})
1	Buffer Layer	GaN or AlGaN/GaN strained superlattice	50~ 500Å	UD (undoped)
2	n-contact	GaN:Si	3-5mm	5×10^{18}-10^{20}
3	Electron injection well	InGaN (In content 28%)	500Å	UD or n-type
4	RTB	GaN	8Å	UD
5	Active well	InGaN (In content 40%)	15Å	UD
6	p-contact	GaN:Mg or GaN:Mg + Al	0.5 μm	~10^{18}

Fig. 3 shows a second structure which is similar to the first but with an extra p-$Al_{0.1}Ga_{x-0.1}$ N electron blocking layer for further reduction of the electron current leakage.

Fig. 5 shows a third structure which is similar to the second but without the p-GaN layer.

The p-$Al_{0.1}$ $Ga_{x-0.1}$ N electron blocking layer serves as a contact. This will reduce the thickness of the p-type layer and improve hole injection into the active layer and light extraction through wide-band gap windows.

5   Fig. 7 shows a fourth structure which is similar to the first, second and third, except an extra polycrystalline GaN layer is deposited to make an efficient p-type ohmic contact.

The illustrated structure is a modified version of the first structure with the extra polycrystalline GaN layer.

10   Fig.8. shows an AlGaInP based LED based on a two well system with charge asymmetric resonance tunnelling. It has an n-type GaAs substrate with a thickness of 100-300 μm and an attached metallic contact. Upon the substrate an n-type GaAs buffer layer is deposited. An n-contact layer is deposited on top of the buffer layer and is made

15   of 0.3 to 1 μm thick n-type $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0.5 \leq x \leq 1$ and a doping level of 5×10^{17} - 10^{20} cm^{-3}. On this layer an electron emitting wide well is epitaxially grown which is formed of a simple undoped layer or a multiple quantum well structure. An undoped electron emitting layer can be made of 0.02 to 0.2 μm thick $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0.2 \leq x \leq 0.5$. A multiple quantum well structure can be made of < 1 μm thick

20    $(Al_xGa_{1-x})_{1-y}In_yP$ / $(Al_{x1}Ga_{1-x1})_{1-y1}In_{y1}P$ with $0.5 \leq x \leq 1$, $0.4 \leq y \leq 0.6$ and $0 \leq x1 \leq 0.4$, $0 \leq y1 \leq 0.4$. Then the charge asymmetric resonance tunnelling barrier is epitaxially deposited, which is made of a 10-100 Å thick undoped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ layer with $0.7 \leq x \leq 1$. The barrier width and height are optimized in such way in order to allow resonant tunnelling of the electrons from the electron injecting wide well layer into the

25   active well and at the same time to block the hole tunnelling from the active well into the electron injecting layer. The active well layer can be either a single quantum well (SQW) structure or multiple quantum well (MQW) structure. An SQW structure can be made of <200 Å thick undoped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0 \leq x \leq 0.4$. An MQW structure can be made of < 3 μm thick $(Al_xGa_{1-x})_{1-y}In_yP$ / $(Al_{x1}Ga_{1-x1})_{1-y1}In_{y1}P$ with $0.5 \leq x \leq 1$, $0.4 \leq$

30    $y \leq 0.6$ and $0 \leq x1 \leq 0.4$, $0 \leq y1 \leq 0.4$. The hole emitting layer is made of p-type $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with $0.5 \leq x \leq 1$. The window layer is made of p-type $In_xGa_{1-x}P$ with $x \leq 0.1$. On the hole emitting layer a metallic ohmic contact is deposited. Table 3 lists

parameters for the AlInGaP LED based on the charge asymmetric resonance tunnelling structure.

Table 3.

5

#	Layer	Composition	Thickness	Doping(cm^{-3})
1	Buffer Layer	n-GaAs	0.1~0.3 mm	$5 \times 10^{17} - 10^{19}$
2	n-contact	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ $0.5 \leq x \leq 1$	0.3~2 mm	$5 \times 10^{17} - 10^{20}$
3	WW	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ $0.2 \leq x \leq 0.5$	100~2000Å	UD or n-type
4	RTB	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ $0.7 \leq x \leq 1$	10~100Å	UD
5	Active QW	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ SQW or MQW	SQW 25~100Å MQW 0.2~1 μm	UD
6	p-Contact	$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ $0.5 \leq x \leq 1$	0.5~2 μm	$5 \times 10^{16} - 10^{18}$
7	Window Layer	$In_xGa_{1-x}P$ $x \leq 0.1$	8~12 μm	$5 \times 10^{17} - 5 \times 10^{18}$

15

Fig. 9 shows a fifth structure which is similar to the first, second, third and fourth, except without the substrate and the ohmic contacts being on the top and bottom of the structure. The extra thick GaN layer is deposited on top of the GaN buffer layer to allow the structure to be free standing after the removal of the sapphire substrate by an

20   excimer laser of 193 or 248 nm UV range.

CLAIMS

1. An LED based on a two well system with charge asymmetric resonance tunnelling, comprising first and second coupled wells, one being a wide well and the other an active quantum well, the wells being coupled via a resonance tunnelling barrier which is transparent for electrons and blocking for holes.

2. An LED according to claim 1 which is a GaN based LED.

3. An LED according to claim 2, wherein the wide well comprises InGaN, the resonance tunnelling barrier comprises GaN and the quantum well comprises InGaN.

4. An LED according to claim 1, wherein the active well is a multiple quantum well structure.

5. An LED according to claim 1, wherein the buffer layer is a strained superlattice.

6. An LED according to claim 1, wherein a p-contact layer is one of GaN, $p\text{-}Al_xGa_{1-x}N$ and p- type polycrystalline GaN.

7. An LED according claim 1, wherein a p-contact layer has been doped by isoelectronic codoping using one or both of Mg and Al.

8. An LED according to claim 1, wherein a substrate is removable or has been removed by wet etching or laser ablation.

9. An LED according to claim 1, wherein ohmic contacts are either both on the top or on the top and bottom of the LED structure.

10. An LED according to claim 1 which is an AlGaInP based LED comprising: